



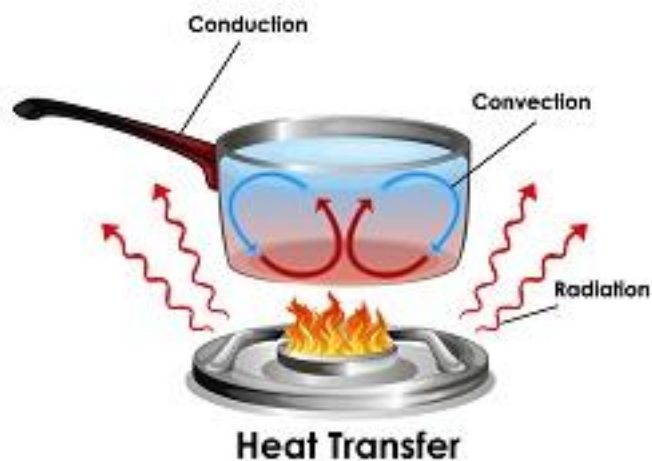
HEAT TRANSFER



Department of Mechanical Engineering



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IMPORTANT QUESTIONS WITH ANSWERS



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Q/1(a) Write down the general three dimensional heat conduction equation in cartesian coordinates. What are the conditions involved. Reduce this equations to Laplace and Poisson's equations. state the conditions for above equations.

Ans: The general heat conduction equation is

$$\frac{\partial}{\partial x} (k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k_z \frac{\partial T}{\partial z}) + q_g = \rho c \frac{\partial T}{\partial t}$$

where $T = f(x, y, z)$

t = time in second

T = temp. in $^{\circ}\text{C}$ or K

k_x, k_y, k_z = Thermal conductivities in x, y, z directions respectively in W/mK

q_g = internal heat generation per unit volume per unit time in W/m^3

ρ = density of the material in kg/m^3

c = specific heat of the substance in J/kgK .

The conditions are:

- (i) Unsteady state heat conduction
- (ii) Non-isotropic (anisotropic) material (k 's not constant).
- (iii) self or internal heat generation



→ Laplace equation is formulated by the conditions that no self or internal heat generation and steady state heat conduction with isotropic material.

→ Laplace equation is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0$$

→ Poisson's equation is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q_g}{k} = 0$$

condition is — steady state with self-heat generation and isotropic material.

Q.11 (b) what are the parameters that influence the convection heat transfer?

- Ans:-
- (i) Thermodynamic and transport properties (viscosity, density, specific heat etc)
 - (ii) Geometry of the surface
 - (iii) Nature of fluid flow
 - (iv) Prevailing thermal conditions.



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Q. (c) what is the physical significance of Nusselt number. How is it related with convection and conduction heat transfer. Hence work out its relationship with the appropriate parameters.

Ans: Nusselt number can be defined in several ways:

(i) It is the ratio of heat flow rate by convection process under a unit temp. gradient to the heat flow rate by conduction process under a unit temp. gradient through a stationary thickness of 1 meter. Thus,

$$Nu = \frac{Q_{\text{convection}}}{Q_{\text{conduction}}} = \frac{h}{k/L} = \frac{hL}{k}$$

(ii) It is the ratio of heat transfer rate, Q , to the rate at which heat would be conducted within the fluid under a temp. gradient of $\Delta T/L$. Thus,

$$Nu = \frac{Q}{(\Delta T \cdot k) / L} = \frac{Q}{\Delta T} \cdot \frac{L}{k} = \frac{hL}{k}$$

(iii) It is the ratio of ~~heat transfer rate~~ characteristic length L to the thickness Δx of a stationary fluid layer conducting the heat at the same rate under the same temp. difference as in the case of convection process.



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$$\text{Thus, } Q = K \frac{A \Delta t}{\Delta x} = h \cdot A \cdot \Delta t$$

$$\text{or } A \Delta x = \frac{K}{h}$$

$$\therefore Nu = \frac{L}{\Delta x} = \frac{L}{K/h} = \frac{hL}{K}$$

→ The Nusselt number is a convenient measure of the convective heat transfer coefficient. For a given value of the Nusselt number, the convective heat transfer coefficient is directly proportional to thermal conductivity of the fluid and inversely proportional to the significant length parameter.

Q11 (d) The inner and outer surfaces of a 0.5 cm thick, 2 m x 2 m window glass in winter are 40°C and 30°C respectively. If the thermal conductivity of the glass is 0.78 W/mK, determine the amount of heat loss through the glass over a period of 5 hours. What would your answer be if the glass were 1 cm thick.

Ans: Given data

$$L = 0.5 \text{ cm} = 0.005 \text{ m}$$

$$A = 2 \text{ m} \times 2 \text{ m} = 4 \text{ m}^2$$

$$T_i = 40^\circ\text{C}$$

$$T_o = 30^\circ\text{C}, K = 0.78 \frac{\text{W}}{\text{m}\cdot\text{K}}$$



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$$Q = \frac{KA(T_1 - T_2)}{L} = \frac{0.78 \times 4 \times (40 - 3)}{0.01}$$

$$= 4868 \text{ W}$$

The amount of heat loss through the glass over a period of 5 hr = $3600 \times 5 = 18000 \text{ sec.}$

$$= 4868 \times 18000 = 78624 \text{ kJ}$$

$$\text{If } L = 1 \text{ cm} = 0.01 \text{ m}$$

$$Q = \frac{0.78 \times 4 \times (40 - 3)}{0.01} \times \frac{18000}{1000} = 39312 \text{ kJ (Ans)}$$

Q.1 (P) what are the physical mechanisms associated with heat transfer by conduction, convection and radiation, what are the transport properties associated with the above modes of heat transfer, state their units.

Ans: Conduction - In solids, heat is conducted by the following two mechanism:

- (i) By lattice vibration the faster moving molecules or atoms in the hottest part of a body transfer heat by impacts some of their energy to adjacent molecules.



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(ii) By transport of free electrons (Free electrons provide an energy flux in the direction of decreasing temp.) For metals, especially good conductors, the electronic mechanism is responsible for the major portion of the heat flux.

→ In case of gases, the kinetic energy of a molecule is a function of temp. These molecules are in a continuous random motion exchanging energy and momentum. When a molecule from a high temp. region collides with a molecule from the low temp. region, it loses energy by collision.

→ In liquids, the mechanism of heat transfer is similar to gases. But the molecules are closely packed and intermolecular forces come into play.

Convection: This mode of heat transfer is met with in situations where energy is transferred as heat to a flowing fluid at any surface over which flow occurs. This mode is basically conduction in a very thin fluid layer at the surface and then mixing caused by the flow. The heat flow depends on the properties of fluid and is independent of the properties of the material of the surface. However, the shape of the surface will influence the flow and hence the heat transfer.



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→ Free or natural convection occurs when the fluid circulates by virtue of the natural differences in densities of hot and cold fluids. In forced convection, work is done to blow or pump the fluid.

Radiation :- Radiation heat is thought of as electro-magnetic waves or quanta or emanation of the same nature as light. These waves carry energy with them and transfer heat to the relatively slow moving molecules of the cold body on which they happen to fall. The molecular energy of the latter increases and results in a rise of its temp.

Q1) (F) What is the difference between mixed and unmixed fluids in cross flow heat exchanger. Show it by neat sketches.

Ans:- In cross-flow heat exchanger, the two fluids (hot and cold) cross one another in space, usually at right angles.

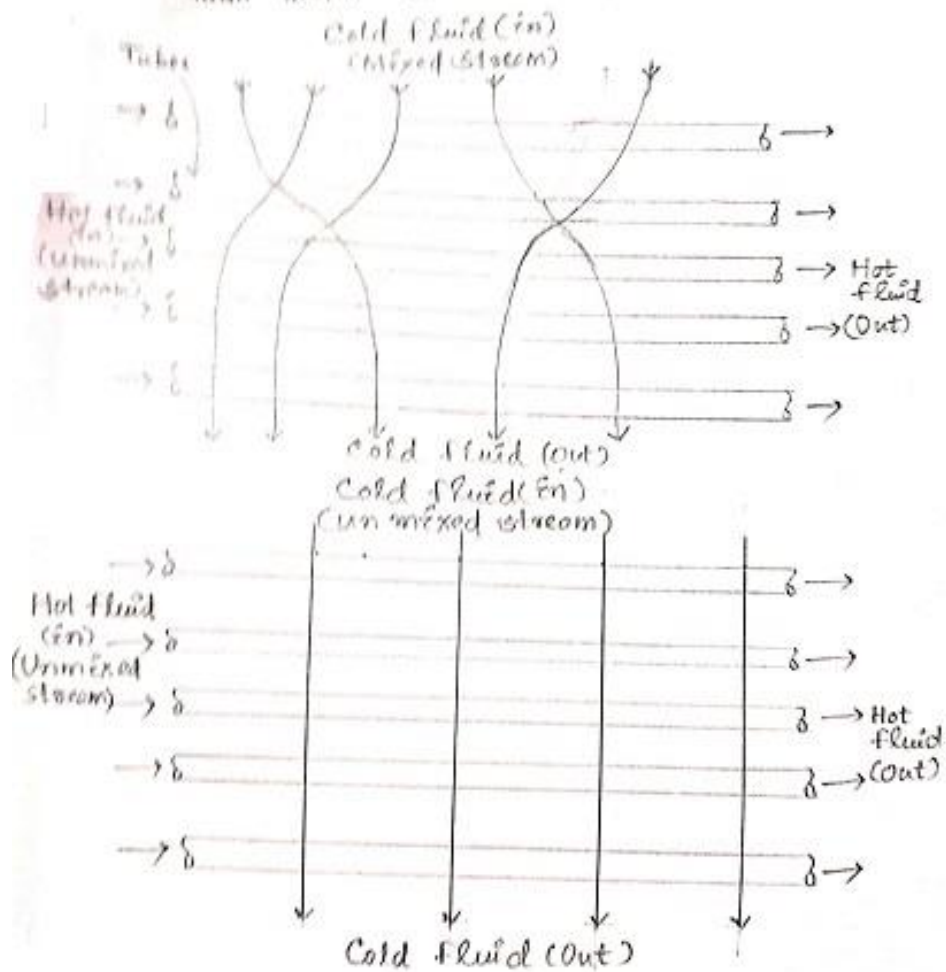
→ In mixed type, hot fluid flows in the separate tubes and there is no mixing of the fluid streams. The cold fluid is perfectly mixed as it flows through the exchanger. The temp. of this mixed fluid will be uniform across any section and will vary only in the direction of flow.



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In unmixed flow, each of the fluids follows a
distinct path and is unmixed as it flows through
the heat exchanger. Here the temp of the fluid leaving the
heat exchanger is not uniform.

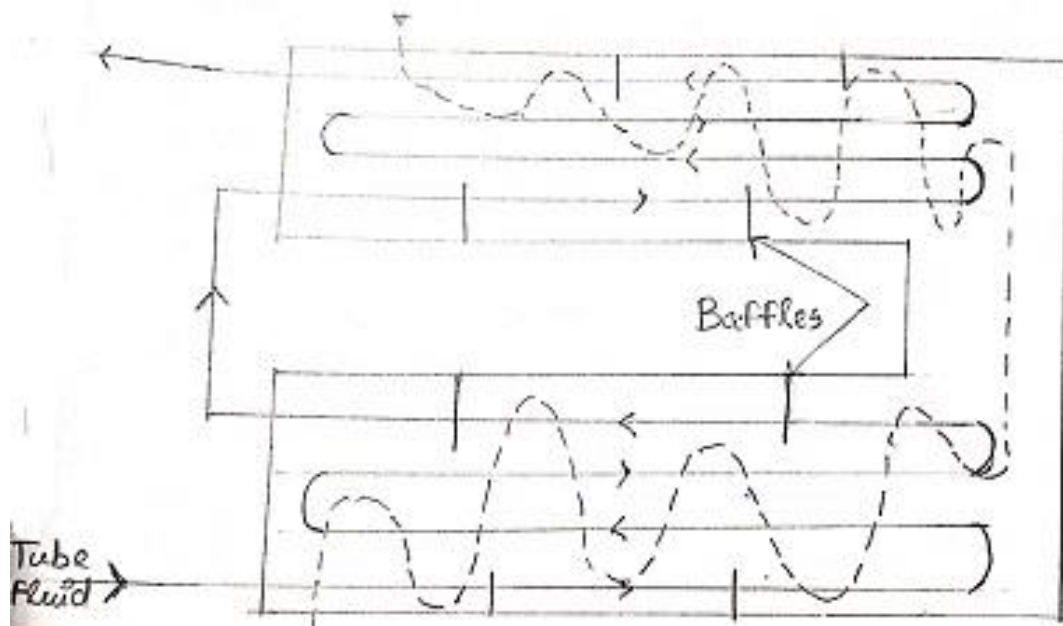




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Q/Kg) Draw a 2 shell pass and 8 tube pass shell and tube heat exchanger.



(Two shell pass and 8 tube pass heat exchanger)



Q1(b) How does transient heat transfer differ from steady state heat transfer. Give me example.

Ans: \rightarrow If the temp is not a function of time i.e. temp don't vary with respect to time, it is said to be steady state heat transfer.

\rightarrow If temp varies with time then it is called transient (unsteady state) heat transfer.

Example - cooling of I.C. engines.

Q2(c) what is the difference between fin efficiency and fin effectiveness?

Ans: \rightarrow Fin efficiency (η_{fin}) is defined as the ratio of actual heat transferred by the fin to the maximum heat transfer by fin, if entire surface area were at base temp

$$\eta_{fin} = \frac{Q_{fin}}{Q_{max}}$$

\rightarrow Effectiveness of fin (ϵ_{fin}) is the ratio of the fin heat transfer rate to the heat transfer rate that would exist without a fin.

$$\epsilon_{fin} = \frac{Q_{with fin}}{Q_{without fin}}$$



η_{fin} and ϵ_{fin} , in case of a fin insulated at the tip are related as,

$$\eta_{fin} = \frac{\sqrt{PhkA_{cs}} (t_b - t_a) \tanh ml}{hPl (t_b - t_a)}$$

$$\epsilon_{fin} = \frac{\sqrt{PhkA_{cs}} (t_b - t_a) \tanh ml}{hA_{cs} (t_b - t_a)}$$

$$\Rightarrow \frac{\epsilon_{fin}}{\eta_{fin}} = \frac{Pl}{A_{cs}}$$

$$\Rightarrow \epsilon_{fin} = \eta_{fin} \times \frac{Pl}{A_{cs}} = \eta_{fin} \times \frac{\text{Surface area of fin}}{\text{Cross-sectional area of fin}}$$

Q 11) what is the difference between pool boiling and flow boiling?

Ans: Pool boiling :- In this case, the liquid above the hot surface is essentially stagnant and its motion near the surface is due to free convection and mixing induced by bubble growth and detachment.

Flow boiling :- This refers to a situation where the fluid motion is induced by external means (and also by free convection and bubble induced mixing). The liquid is pumped and forced to flow.



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Q11 (a) Define contact resistance and name four important factors that affect the contact resistance.

Ans: Thermal contact resistance is defined as a resistance to heat flow at the interfaces of two contact layers.

→ It develops when two conducting surfaces don't fit tightly together and a thin layer of fluid is trapped between them.

→ The four factors that affect the contact resistance are.

- (i) surface roughness.
- (ii) the pressure holding the two surfaces in contact.
- (iii) the interface fluid.
- (iv) the interface temperature.

Q11 (b) Write down two dimensional heat conduction equation for a homogeneous isotropic material in rectangular co-ordinate system.

Ans:
$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{q}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$



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where T is the temperature $= f(x, y)$

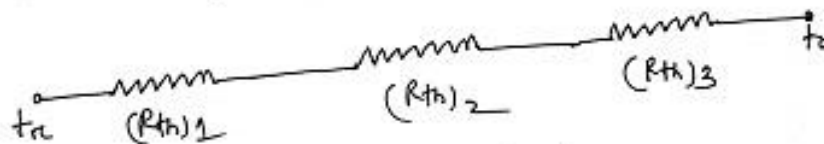
t = time

k = thermal conductivity of the material

q_g = internal heat generation per unit volume per unit time.

α = thermal diffusivity $= \frac{k}{\rho c}$

Q. (6) Draw the thermal circuit for heat transfer between an nuclear reactor and the operator working near its vicinity.



where t_r = Radiator temp.
 t_o = surrounding temp.

$(R_{th})_1$ = Thermal resistance (conductive)

$(R_{th})_2$ = Thermal resistance (convective)

$(R_{th})_3$ = Thermal resistance (radiative)

R_e = equivalent thermal resistance
 $= (R_{th})_1 + (R_{th})_2 + (R_{th})_3$



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Q1) (d) The heat transfer co-efficient for a gas flowing over a thin flat-plate 3 m long and 0.3 m wide varies with distance from the leading edge according to

$$h(x) = 10 x^{-0.25} \text{ W/m}^2\text{K}$$

Find the average heat transfer coefficient.

Ans: Average heat transfer coefficient = $\frac{1}{A} \int h \, dA$

Let dx = distance (length) from the leading edge where 'h' to be calculated.

$$\therefore \text{Average heat transfer coefficient} = \frac{1}{A} \int 10 x^{-0.25} \, dA$$

$$= \frac{1}{3 \times 0.3} \int_{0.3} 10 x^{-0.25} \, dx$$

$$= \frac{1}{3} \int 10 x^{-0.25} \, dx$$

$$= \frac{10}{3} \left[\frac{x^{-0.25+1}}{-0.25+1} \right]_0^3 = \frac{10}{3 \times 0.75} [3^{0.75}]$$

$$= 10.13 \text{ W/m}^2\text{K} \quad (\text{Ans})$$



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Q11 (e) why higher rate of heat transfer is experienced in drop wise than in film condensation?

Ans: 2019 - Q. 3 (e)

Q11 (f) what advantages does the effectiveness-NTU method have over LMTD method?

Ans: \rightarrow A heat exchanger can be designed by the LMTD (logarithmic mean temp. difference) when inlet and outlet conditions are specified. However, when the problem is to determine the inlet or exit temp. for a particular heat exchanger, the analysis is performed more easily, by using a method based on effectiveness of the heat exchanger and number of transfer units (NTU). This method is known as NTU method.

\rightarrow This method facilitates the comparison between the various types of heat exchangers which may be used for a particular application.



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Q1 (i) Distinguish between a black body and a grey body.
Ans: \rightarrow A black body is an object that absorbs all the radiant energy reaching its surface. So for a black body α (absorptivity) $= 1$
 ρ = reflectivity $= 0$, τ = transmissivity $= 0$

\rightarrow A grey body is one in which the radiative properties are assumed to be uniform over the entire wavelength spectrum. $\alpha = (\alpha)_\lambda = \text{constant}$. i.e. ' α ' does not vary with temp. and wavelength of the incident radiation.

Q1 (ii) Define Prandtl number and state its significance.

Ans: \rightarrow Prandtl number is defined as the ratio of kinematic viscosity (ν) to thermal diffusivity (α)

$$\text{i.e. } Pr = \frac{\mu c_p}{k} = \frac{\frac{\mu}{\rho} \cdot \frac{1}{\rho c_p}}{\frac{k}{\rho c_p}} = \frac{\nu}{\alpha}$$

\rightarrow It provides a measure of relative effectiveness of the momentum and energy transport by conduction process (diffusion)



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→ it is a connecting link between velocity field and temperature field, and its value strongly influences relative growth of velocity and thermal boundary layers.



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Q/10/ How heat is transferred from one body to other in conduction mode?

Ans:- Heat is transferred from one body to other by two mechanisms:

- By lattice vibrations (the faster moving molecules or atoms in the hottest part of a body transfer heat by impacting some of their energy to adjacent molecules).
- By transport of free electrons (Free electrons provide an energy flux in the direction of decreasing temp.).
- But in gases, the K.E. of molecules is a function of temp. when a molecule of higher temp. region collides with low temp. region, it loses energy by collision.
- In liquids the mechanism of heat conduction is nearer to that of gases.



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Q11 (b) What is thermal diffusivity and what does it signify?

Ans: Thermal diffusivity (α) is defined as the ratio between thermal conductivity (k) and thermal capacity (ρC_p)

$$\text{or } \alpha = \frac{k}{\rho C_p} = \frac{\text{Thermal conductivity}}{\text{Thermal capacity}}$$

- The larger the value of α , the faster will the heat diffuse through the material and its temp. will change with time. This will result either due to high value of thermal conductivity k or a low value of heat capacity ρC_p .
- A low value of heat capacity means the less amount of heat entering the element, would be absorbed and used to raise its temp. and more would be available for onward transmission.
- Metals and gases have relatively high value of α and the non-metallic solids and liquids have relatively small value of α .



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Q/1 (c) Write the governing equation for a 3-D steady, constant property heat conduction equation.

Ans:- Governing equation for 3-D steady, constant property heat conduction equation.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q_g}{k} = 0$$

where $T = \text{temp.} = f(x, y, z)$

$q_g = \text{internal or self heat generation per unit volume per unit time}$

$k = \text{thermal conductivity of the material}$

Q/1 (d) what is the criterion for a fin to be considered as a long fin?

Ans:- see ans 2013 — 1 (d).

Q/1 (e) what happens to the conductivity of a gas when its temperature increases and why?

Ans:- The thermal conductivity of a gas increases with



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increase in temperature. This is because the mean molecular path of gas molecules decreases with increase in density and 'K' is directly proportional to the mean free path of molecule.

Q/ (f) For fluids during Prandtl number greater than 1 which boundary layer thickness is greater and why?

Ans: When $Pr > 1$ hydrodynamic boundary layer thickness is greater than thermal boundary layer. $\delta > \delta_{th}$, because at $Pr > 1$ heat diffusion is very slow relative to momentum.

Q/ (g) What is Rayleigh Number and what is its significance?

Ans: Rayleigh number (Ra) is a dimensionless number associated with buoyancy-driven flow, also known as free convection.

$$Ra = Gr \times Pr$$

where Gr - Grashof number, Pr - Prandtl number.



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→ When the Rayleigh number is below a critical value for a fluid, heat transfer is primarily in the form of conduction, when it exceeds the critical value, heat transfer is primarily in the form of convection.

Q11 (b) What is meant by 'fully developed flow condition' in flow through pipes?

Ans: 2019 — Q2 4(C)

Q11 (b) Define a 'diffused reflection' and how it is different from a specular reflection?

Ans: → If the surface has some roughness, the incident radiation is scattered in all directions after reflection. Such reflection is called the diffused reflection.

→ If the surface is perfectly smooth and the angle of incident and angle of reflected rays are equal, then it is called specular reflection.



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Q4) Define a 'compact heat exchanger' and give one example.

Ans: 2014 - Q 4) (5)



1. (a) How steady state heat conduction differs from transient heat conduction?

Ans :- Conduction of heat in steady state refers to the steady conditions wherein the heat flow and the temp. distribution at any point of the system does not vary with time.

Conduction of heat in unsteady or transient state refers to the unsteady conditions wherein the heat flow and temp distribution at any point of the system vary continuously with time.

(b) Why a good conductor of electricity is also a good conductor of heat?

Ans :- According to Wiedemann and Franz law :- "The ratio of thermal and electrical conductivities is the same for all metals at the same temp and the ratio is directly proportional to the absolute temp of metal."

Mathematically $\frac{k}{\sigma T} = C$



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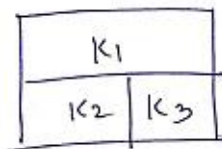
Where k = Thermal conductivity of metal at temp T (K)

σ = Electrical conductivity of metal at temp T (K)

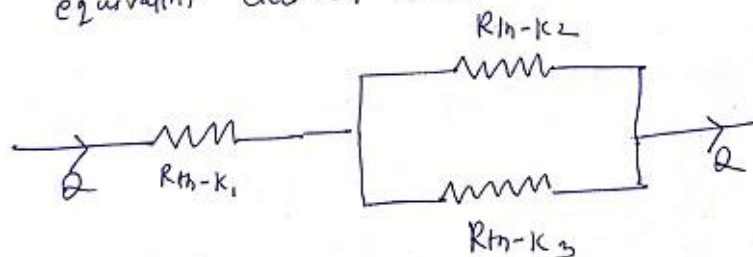
C = Constant (also known as Lorenz Number)

From the above expression " $k = C \sigma T$ ", it is clear that a good conductor of electricity is also a good conductor of heat.

(c) Draw the equivalent electrical circuit of the following system and find the equivalent conductivity.



equivalent electrical circuit:



$$\text{equivalent conductivity } (k_E) = R_{th-k_1} + \left(\frac{R_{th-k_2} \times R_{th-k_3}}{R_{th-k_2} + R_{th-k_3}} \right)$$



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(d) when a fin is considered to be a long fin?

Ans:- A fin is considered to be a long fin when

$$ml > 5$$

$$\text{where } m = \text{constant} = \sqrt{\frac{hp}{kA_{cs}}}$$

l = length of fin

h = heat transfer coefficient (convective)

p = perimeter of the fin

k = Thermal conductivity of the fin (constant)

A_{cs} = Area of cross-section.

(e) why dropwise condensation is preferred over filmwise condensation?

Ans:- Refer 2014 question - 1 (e)

(f) Ans:- Refer 2014 question - 1 (c)

(g) Ans:- Refer 2014 question - 1 (f)



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(R) Write two methods of minimizing the radiation heat loss.

Ans: Methods of minimizing the radiation heat loss:

(i) By using highly reflective materials between the heat exchanging surfaces.

(ii) By using radiation shields between the heat exchanging surfaces.

(i) Why counterflow heat exchanger is more effective than parallel flow heat exchanger?

Ans: In counterflow heat exchanger, the temperature difference between the two fluids remains more or less nearly constant.

→ We know $Q = UA \text{ LMTD}$

$$\text{LMTD}_{(\text{Counterflow})} > \text{LMTD}_{(\text{parallelflow})}$$

$$\text{So } Q_{\text{counter}} > Q_{\text{parallel}}$$

So counterflow heat exchanger gives maximum rate of heat transfer for a given surface area. So counterflow heat exchanger is more effective than parallel flow heat exchanger.



(j) Define a grey surface.

Ans :- A gray surface is defined as one whose absorptivity of the surface does not vary with temp. and wavelength of the incident radiation.

→ Also a gray surface can be defined as a surface whose radiative properties are assumed to be uniform over the entire wavelength spectrum.



1. (a) Why gas has lower thermal conductivity than solid?

Ans :- Thermal conductivity in a substance relies on collisions of molecule within the substance. In gases molecules much more widely spaced than in a solid, the collisions are less and it takes longer to energy propagate that's why gas has lower thermal conductivity than solid.

(b) What is the difference between fin effectiveness and fin efficiency?

Ans :- Effectiveness of fin is the ratio of the fin heat transfer rate to the heat transfer rate that would exist without fin.

Efficiency of a fin is defined as the ratio of the actual heat transferred by the fin to the maximum heat transferable by fin, if entire fin area were at base temperature.



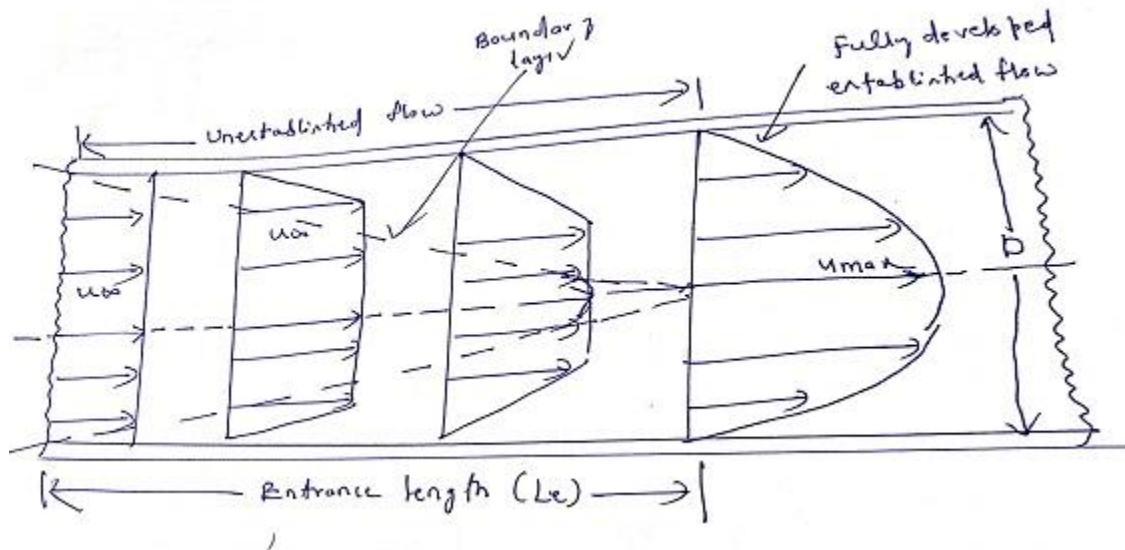
(c) what is fully developed flow condition for a flow through tube?

Ans - In case of a pipe flow, the development of boundary layer proceeds in a fashion similar to that for flow along a flat plate. A fluid of uniform velocity entering a tube is retarded near the walls and a boundary layer begins to develop as shown in the fig by dotted lines. The thickness of the boundary layer is limited to the pipe radius because of the flow being within a confined passage. Boundary layers from the pipe walls meet at the centre of the pipe and the entire flow acquires the characteristics of a boundary layer. Once the boundary layer thickness becomes equal to the radius of the tube there will not be any further change in the velocity distribution, this invariant velocity distribution is called fully developed velocity profile.

According to Langhaar, the entrance length (L_e) is expressed as: $\frac{L_e}{D} = 0.0575 Re$ where D represents the inside diameter of the pipe.



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(d) What is Newton's law of viscosity and thus define an ideal fluid.

Ans. This law states that the shear stress (τ) on fluid element layers is directly proportional to the rate of shear strain. The constant of proportionality is called the coefficient of viscosity.

$$\text{Mathematically, } \tau = \mu \frac{du}{dy}$$

The fluids which follow this law are known as Newtonian fluids.

An ideal fluid is one which has no viscosity and surface tension and is incompressible. In true sense no such fluid exists in nature.

However, fluids which have low viscosities such as water and air can be treated as ideal fluids under certain conditions. The assumption of ideal fluids helps in simplifying the mathematical analysis.



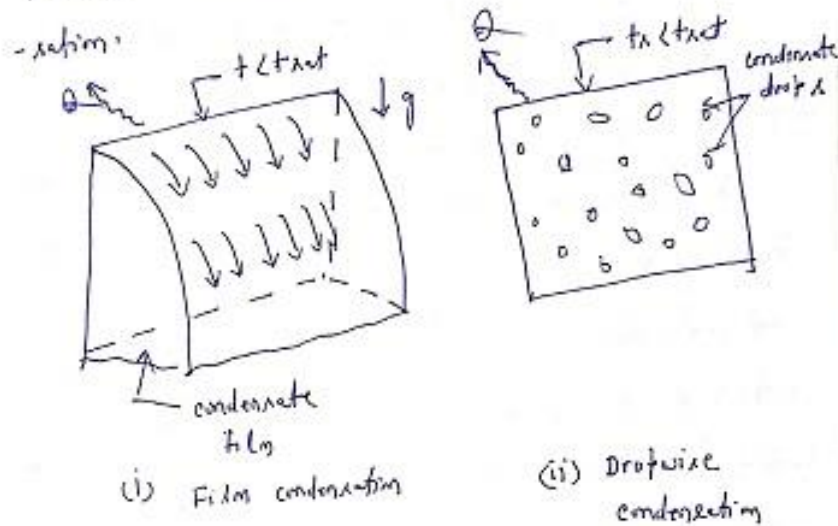
Q) Which type of condensation is preferable and why?

Ans: If the condensate tends to wet the surface and thereby forms a liquid film, then the condensation process is known as 'film condensation'. Here, the heat from the vapour to the cooling medium is transferred through the film of the condensate formed on the surface. The liquid flows down the cooling surface under the action of gravity and the layer continuously grows in thickness because of newly condensing vapour. The continuous film offers thermal resistance and checks further transfer of heat between the vapour and the surface.

Further, the heat transfer from the vapour to the cooling surface takes place through the films formed on the surface. The heat is transferred from the vapour to the condensate formed on the surface by 'convection' and it is further transferred from the condensate film to the cooling surface by the conduction.



This combined mode of heat transfer by conduction and convection reduces the rate of heat transfer considerably (compared with dropwise condensation). That is the reason that heat transfer rates of filmwise condensation are lower than dropwise condensation.



< Film and dropwise condensation on a vertical surface >

in 'dropwise condensation' the vapour condenses into small liquid droplets of various sizes which fall down the surface in random fashion.



The drops form in cracks and pits on the surface, grow in size, break away from the surface, knock off other droplets and eventually run off the surface, without forming a film under the influence of gravity. Fig (ii) shows the dropwise condensation on a vertical plate.

In this type of condensation, a large portion of the area of solid surface is directly exposed to vapour without an insulating film of condensate liquid, consequently higher heat transfer rate (to the order of 750 kW/m²) are achieved. Dropwise condensation has been observed to occur on highly polished surfaces. This type of condensation gives coefficient of heat transfer generally 5 to 30 times larger than with film condensation.

That is why dropwise condensation is preferred to filmwise condensation.



(f) Write the significance of Grashoff number, in respect of natural convection.

Ans :- Grashoff number is related with natural convection heat transfer. It is defined as the ratio of product of inertial force and buoyancy force to the square of viscous force. Thus

$$Gr = \frac{(\text{Inertial force}) \times (\text{Buoyancy force})}{(\text{Viscous force})^2}$$
$$= \frac{(\rho v^2 L^2) \times (\rho \beta g \Delta T L^3)}{(\mu v L)^2}$$

$$\Rightarrow Gr = \frac{\rho^2 \beta g \Delta T L^3}{\mu^2}$$

Grashoff number has a role in free convection similar to that played by Reynolds number in forced convection. Free convection is usually suppressed at sufficiently small Gr , begins at some critical value of Gr depending upon the arrangement and then becomes more and more effective with increasing Gr .



g) Show that for an ideal fluid $\beta = 1/T$ where β is the volumetric coefficient of thermal expansion and T is in K.

Ans - A property that comes into play in free or natural convection is the coefficient of thermal expansion of the fluid defined by

$$\beta = \frac{1}{v} \left(\frac{\partial v}{\partial T} \right)_p$$

For an ideal gas $p v = R T$

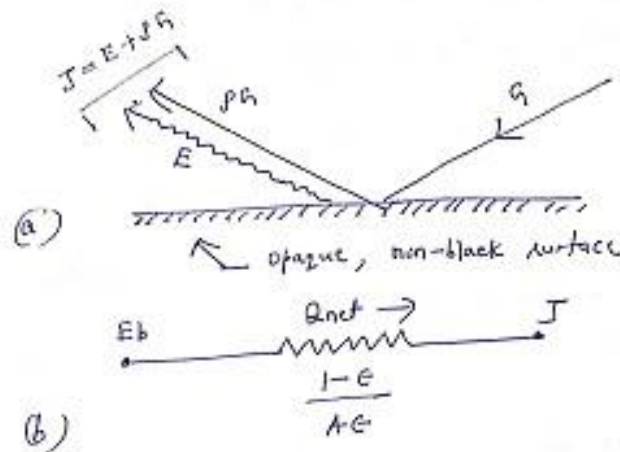
$$\Rightarrow v = \frac{R T}{p} \Rightarrow \left(\frac{\partial v}{\partial T} \right)_p = \frac{R}{p}$$

$$\text{So } \beta = \frac{p}{R T} \times \frac{R}{p} = \frac{1}{T} \quad (\text{Agn})$$



(b) what is the 'surface resistance' and 'space resistance' in respect of radiation exchange between two surfaces?

Ans:-



An electrical network analogy is an approach for analyzing radiation heat exchange between gray or black surfaces. In this approach the two terms commonly used are irradiation and radiosity.

irradiation $\div (G)$:- It is defined as the total radiation incident upon a surface per unit time per unit area. It is expressed in W/m^2 .



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Radiosity (J) :- This term is used to indicate the total radiation leaving a surface per unit time per unit area. It is also expressed in W/m^2 .

The radiosity combines the original emittance E from the surface plus the reflected portion of any radiation incident upon it. [Refer fig (a)]

$$\text{i.e.} \quad J = E + \rho G$$

$$\Rightarrow J = \epsilon E_b + \rho G$$

where, E_b = Emissive power of a perfect black body at the same temp.

$$\text{Also,} \quad \alpha + \rho + \tau = 1$$

$$\Rightarrow \alpha + \rho = 1 \quad \langle \tau = 0, \text{ the surface being opaque} \rangle$$

$$\Rightarrow \rho = 1 - \alpha$$

$$\therefore J = \epsilon E_b + (1 - \alpha) G$$

$$\text{But } \alpha = \epsilon \quad \dots\dots \text{B) Kirchhoff's law}$$

$$\Rightarrow J = \epsilon E_b + (1 - \epsilon) G$$

$$\text{or } J - \epsilon E_b = (1 - \epsilon) G$$

$$\Rightarrow G = \frac{J - \epsilon E_b}{1 - \epsilon}$$



The net energy leaving a surface is the difference between its radiosity and irradiation. Thus

$$\begin{aligned} \frac{Q_{net}}{A} &= J - G \\ \Rightarrow \frac{Q_{net}}{A} &= J - \frac{J - \epsilon E_b}{1 - \epsilon} \\ &= \frac{J(1 - \epsilon) - (J - \epsilon E_b)}{1 - \epsilon} \\ &= \frac{J - J\epsilon - J + \epsilon E_b}{1 - \epsilon} = \frac{\epsilon(E_b - J)}{1 - \epsilon} \\ \text{or } Q_{net} &= \frac{A\epsilon(E_b - J)}{1 - \epsilon} = \frac{E_b - J}{(1 - \epsilon)/A\epsilon} \end{aligned}$$

The representation of this equation in the form of electric network is shown in fig (b). The quantity $\frac{1 - \epsilon}{A\epsilon}$ is known as surface resistance, as it is related to surface properties of the radiating body.



HEAT TRANSFER



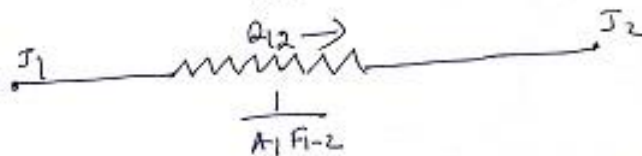
consider the exchange of radiant energy between the two surfaces (non-black) 1 and 2. of the total radiation which leaves surface 1, the amount that reaches surface 2 is $J_1 A_1 F_{1-2}$. Similarly the heat radiated by surface 2 and received by surface 1 is $J_2 A_2 F_{2-1}$. The net interchange of heat between the surfaces (Q_{12}) is given by

$$Q_{12} = J_1 A_1 F_{1-2} - J_2 A_2 F_{2-1}$$

But $A_1 F_{1-2} = A_2 F_{2-1} \dots$ By reciprocity theorem

$$\therefore Q_{12} = A_1 F_{1-2} (J_1 - J_2)$$

$$\text{or } Q_{12} = \frac{J_1 - J_2}{1/A_1 F_{1-2}}$$



The above equation can be represented in the form of electric network as shown in the figure. The quantity $\frac{1}{A_1 F_{1-2}}$ is called the space resistance because it is due to the distance and geometry of the radiating bodies.



(i) What is the surface temperature of sun and how is it estimated?

Ans:- The sun is assumed to be a black body emitting radiation with maximum intensity at $\lambda = 0.49 \mu\text{m}$

According to Wien's displacement law

$$\lambda_{\text{max}} T = 2898 \mu\text{mK}$$

$$\Rightarrow T = \frac{2898}{\lambda_{\text{max}}} = \frac{2898}{0.49} = 5914 \text{ K}$$

So surface temp. of sun is 5914 K (approx)



(i) What is a compact heat exchanger? Give one example

Ans:- A heat exchanger having a large surface area per unit volume is called a compact heat exchanger.

The ratio of the heat transfer surface area to the volume is called the area density β . A heat exchanger with $\beta > 700 \text{ m}^2/\text{m}^3$ is said to be compact, examples:- car radiator ($\beta = 1000 \text{ m}^2/\text{m}^3$), ceramic regenerator in gas turbine ($\beta = 6000 \text{ m}^2/\text{m}^3$), and Stirling engine regenerator ($\beta = 15,000 \text{ m}^2/\text{m}^3$).

→ The large surface area is obtained by attaching closely spaced thin plates to the walls separating the two fluids. Compact heat exchangers are commonly used in gas to gas or gas to liquid heat transfer, with limitations on their weight and volume. With fins, if any, being used on the gas side where heat transfer coefficient is low. In compact heat exchangers the two fluids usually move perpendicular to each other, and such flow configuration is called cross-flow.



HEAT TRANSFER



Q.1) How are Fourier's law and Ohm's law similar?

Ans. → When two physical systems are described by similar equations and have similar boundary conditions, these are said to be analogous or similar.

→ The heat transfer processes may be compared by analogy with the flow of electricity in an electrical resistance.

→ As the flow of electric current in the electrical resistance is directly proportional to potential difference (dv); similarly heat flow rate Q is directly proportional to temp. difference (dt)., the driving force for heat conduction through a medium.

→ As per Ohm's law (in electric circuit theory), we have,

$$\text{Current (I)} = \frac{\text{Potential difference (dv)}}{\text{Electrical resistance (R)}}$$

By analogy, the heat flow equation (Fourier's equation) may be written as,

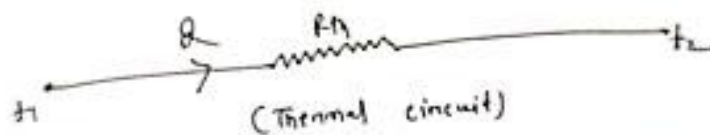
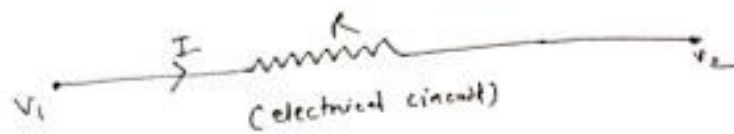
$$\text{Heat flow rate (Q)} = \frac{\text{Temp. difference (dt)}}{\frac{dx}{KA}}$$



HEAT TRANSFER



→ By comparing both the equations, we find that I is similar to θ , $d\theta$ is similar to dt and R is similar to the quantity $\left(\frac{d\theta}{KA}\right)$. The quantity $\frac{d\theta}{KA}$ is called thermal conduction resistance.



Q.11(b) Why are metals good thermal conductors, while non-metals are poor conductors of heat?

- In non-metals heat is conducted only by lattice vibrations.
- In metals heat is conducted both by lattice vibrations and free electrons which are better conductors than atoms.
- Hence metals are good thermal conductors than non-metals.



HEAT TRANSFER



Q11 (c) Define fin effectiveness. when is the use of fins not justified?

Ans: → Effectiveness of fin is defined as the ratio of heat transfer by fin to heat transfer with out fin.

→ When the term $\frac{PK}{hA_{cs}} < 5$, then use of fin is not

Justified

where, P = perimeter of fin in metre

K = Thermal conductivity of fin material in W/mK

h = convective heat transfer coefficient in $\frac{W}{m^2K}$

A_{cs} = cross-sectional area of fin

Q11 (d) How do viscosity of liquid and gas vary with temperature?

Ans: The viscosity of liquid decreases with ^{increasing} temp. because the cohesive forces reduce simultaneously increasing the rate of molecular interchange.



HEAT TRANSFER



→ But the viscosity of gas increases with increase in temp because there is increase in the molecular interchange as molecules move faster in high temperature.

$$\mu = \mu_0 \left(\frac{1}{1 + \alpha t + \beta t^2} \right) \text{ for liquids}$$

$$\mu = \mu_0 + \alpha t + \beta t^2 \text{ for gases}$$

→ where α and β are constant and t is the temp.
 μ_0 is viscosity at 0°C .

Q4 (c) what do you mean by hydraulic ~~boundary~~ boundary layer and thermal boundary layer?

→ The region of the flow over the surface bounded by (defined as a distance from the surface at which local velocity of fluid is 99% of free stream velocity) in which the effects of viscosity shearing forces caused by fluid viscosity are observed, is called hydraulic or velocity or hydrodynamic boundary layer.

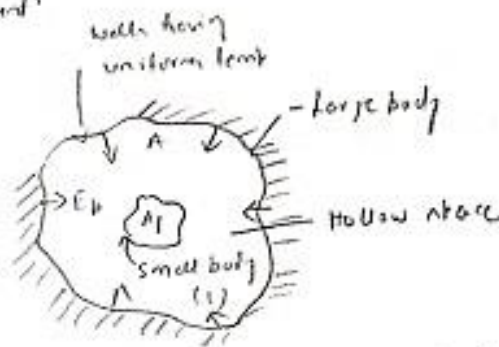
→ The flow region over the surface in which temp. variation in the direction, normal to the surface is observed is called thermal boundary layer.



HEAT TRANSFER



- (*) State and prove Kirchhoff's law of heat radiation.
- The law states that at any temperature the ratio of total emissive power E to the total absorptivity α is a constant for all substances which are in thermal equilibrium with their environment.



Let us consider a large radiating body of surface area A which encloses a small body (1) of surface area A_1 . Let the energy fall on the unit surface of the body at the rate E_b . of this energy generally a fraction α_1 will be absorbed by the small body. Thus this energy absorbed by the small body (1) is $\alpha_1 A_1 E_b$. in which α_1 is the absorptivity of the body. when thermal equilibrium is attained, the energy absorbed by the body (1) must be equal to the energy emitted, say E_1 per unit surface. Thus at equilibrium we may write.

$$A_1 E_1 = \alpha_1 A_1 E_b$$



HEAT TRANSFER



Now we consider body (1) and reflect it by body (2) having absorptivity α_2 . The radiative energy impinging on the surface of this body is again E_b . In this case we may write:

$$A_1 E_b = \alpha_2 A_2 E_b$$

By considering geometry of bodies, we obtain

$$E_b = \frac{E_1}{A_1} = \frac{E_2}{A_2} = \frac{E}{2}$$

and, as the definition of emissivity ϵ , we have

$$\epsilon = \frac{E}{E_b}$$

$$\text{or } E_b = \frac{E}{\epsilon}$$

$$\Rightarrow \epsilon = \alpha$$

α is always smaller than 1. Therefore E is always $< E_b$

Thus Kirchhoff's law also states that the emissivity of a body is equal to its absorptivity when body remains in thermal equilibrium with its surroundings.



HEAT TRANSFER



Q1/2) state and explain reciprocity theorem in radiation heat transfer case.

Ans:- F_{1-2} is the shape factor of A_1 with respect to area A_2 defined as "The fraction of radiative energy that is emitted from the surface A_1 and strikes the surface A_2 with no intervening reflections

$$F_{1-2} = \frac{1}{A_1} \iint_{A_1 A_2} \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{r^2}$$

$$F_{2-1} = \frac{1}{A_2} \iint_{A_2 A_1} \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{r^2}$$

$$\Rightarrow A_1 F_{1-2} = A_2 F_{2-1}$$

$$\text{and } Q_{1-2} = A_1 F_{1-2} \sigma (T_1^4 - T_2^4) \\ = A_2 F_{2-1} \sigma (T_1^4 - T_2^4)$$

The above result $A_1 F_{1-2} = A_2 F_{2-1}$ is known as reciprocity theorem.

Q1/ b) Differentiate between surface and space resistance

Ans:- 2014 - Q) 4 (b).



Q// (i) what do you mean by fouling factor? what are the causes of fouling?

Ans: The reciprocal of scale heat transfer coefficient is called fouling factor (R_f) i.e. $R_f = \frac{1}{h_s}$.

Fouling factors are determined experimentally by testing the heat exchanger in both clean and dirty conditions.

$$R_f = \frac{1}{h_s} = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}}$$

Causes

- (i) Deposition of solid particles suspended in the flowing fluids.
- (ii) Deposition of ash particles in flue gases.
- (iii) chemical fouling due to chemical process industries.